

HOW IT WORKS

GPS navigation

The global positioning system has made it easy to pinpoint your exact location, but how does it do it?

Tom Royal investigates the satellite technology that puts you in the right place at the right time

In this month's *Labs* section on page 177, we've reviewed 16 car navigation systems. These allow you to plan a route, pinpoint your car's location and follow a set of voice prompts that guide you to your destination, be it an address hundreds of miles away or the nearest supermarket. These devices are small, simple to use and remarkably cheap, considering they're based on satellite technology. Here we explain the NAVSTAR Global Positioning System, or GPS, which makes them tick.

RADIO DAYS

The GPS uses a constellation of 24 satellites orbiting the earth, which has cost the United States an estimated \$14 billion (around £8 billion) to launch and maintain. However, the principles on which it is based come from the far simpler technology of radio positioning.

The idea of using radio signals to locate the position of a vehicle or object was first exploited during World War II. The British GEE system, introduced in 1942, used a series of fixed radio transmitters and onboard oscilloscopes to help aircraft navigate over Europe.

The system used several stations on the ground to transmit carefully timed pulses. By timing the arrival of the pulses from a pair of ground

stations, a navigator could work out the relative distance of his aircraft from each station. If the two arrived simultaneously, both stations had to be equally distant, so the aircraft lay on a straight line between the two. If there was a difference in the times of arrival, the aircraft could be anywhere on a hyperbola between the two. By performing the same calculation using a different pair of transmitters, a second line could be drawn and the aircraft would be located at the point where the two lines intersected.

As it works in two dimensions only, the mathematics required to model such a system is relatively simple. If (x, y) is the location of the first transmitter, t_1 is the measured time taken for the signal to pass from the transmitter to receiver, c is the speed of the radio wave and e is the error in the measured time due to differences between the aircraft clock and that at the transmitter, then the equation looks like this:

$$t_1 = \frac{\sqrt{(x-x_1)^2 + (y-y_1)^2}}{c} + e$$

As this equation has three unknown variables (x , y and the error e), it requires three sets of data to

solve. With the times from two more transmitters (t_2 and t_3) and their coordinates (x_2, y_2, x_3, y_3) , you get three simultaneous equations, which can then be solved to calculate the error and exact location of the aircraft. In practice, the GEE system had a range of around 400 miles, and was succeeded by the American LORAN system with a range of around 1,200 miles.

LOST IN SPACE

The USSR launched the first artificial satellite, Sputnik 1, in October 1957. Sputnik carried radio transmitters, and researchers at John Hopkins University soon noted that its radio broadcasts were varying in frequency because of the Doppler effect. Just as the frequency of a siren moving towards a listener appears higher in pitch, as Sputnik passed towards the receiving station the radio waves would compress, reducing the wavelength and increasing the perceived frequency. As it passed overhead and away again, the waves would spread out, producing a reduction in the perceived frequency. By analysing the data from Sputnik 1 and its successor, Sputnik 2, scientists were able to predict the path of each satellite and anticipate each orbit.

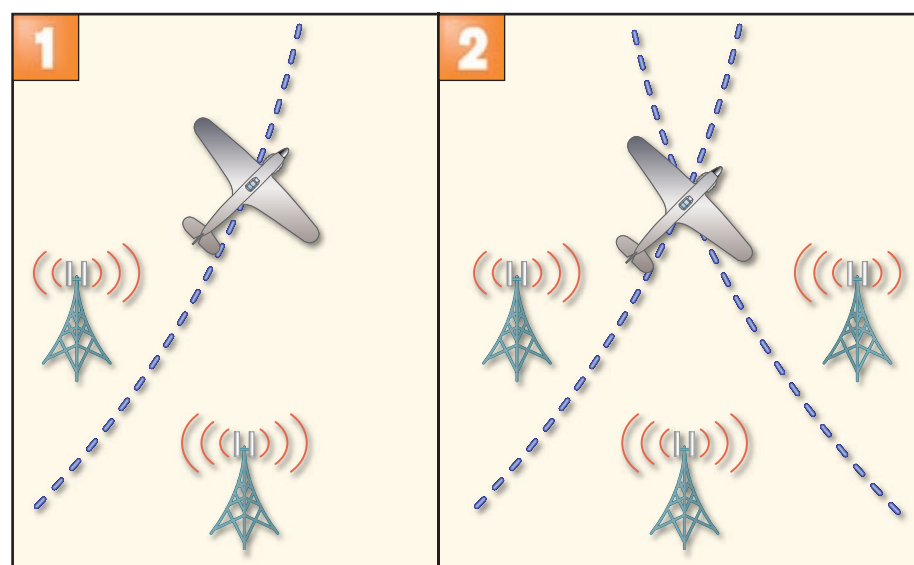
The principle of using the Doppler effect to predict the unknown orbit of a satellite from a known location was reversed to provide the basis of the first satellite navigation systems. The American TRANSIT navigation system, implemented in the 1960s, required at least three satellites and was designed primarily to aid the navigation of submarines. The satellites were monitored by four ground-tracking stations. These stations located the exact position and orbit of each satellite, and updated them with this information regularly.

To ascertain its location, the receiver needed to take several readings from a single TRANSIT satellite as it passed overhead. Every two minutes, the satellite would broadcast its orbit and position. Using this information, and by measuring the Doppler effect on the signal as the satellite passed overhead, the receiver could determine its location in two dimensions: latitude and longitude.

However, compared to the current GPS, TRANSIT was limited. It was less accurate than GPS and, more importantly, coverage was not continuous. With only a few satellites in orbit, receivers might have no way of ascertaining their location for several hours at a time. The TRANSIT system was finally disabled in 1996.

The foundations of the modern GPS were laid during the 1960s as several US military groups examined the possibility of a more accurate satellite navigation system. Various designs, including an enhanced version of TRANSIT, were

2D RADIO NAVIGATION



1 By examining the different time of arrival of signals from two radio transmitters, the navigator knows that his aircraft must lie on a certain hyperbola between the two

2 By using a second pair of transmitters, the navigator is able to plot a second hyperbola. The aircraft must lie where the two lines cross, as the above image shows



suggested by groups within the US Navy and Air Force. By December 1973, a compromise scheme that incorporated elements of several designs was approved by the Defence Acquisition and Review Council (DSARC). This system, using 24 satellites placed in 12-hour orbits, forms the basis of the NAVSTAR GPS in use today.

NAVSTAR QUEST

The first satellite for the new NAVSTAR GPS was launched in 1974, with 11 more launched between 1978 and 1985 for testing purposes. The full constellation of 24 satellites required for constant worldwide coverage and accuracy was completed in December 1993.

NAVSTAR GPS uses satellites in six orbital paths around the earth, each at an altitude of 12,600 miles. As with the TRANSIT system, they are provided with accurate information about their location by a number of observatories on the ground, and this information is constantly rebroadcast. Each satellite carries an atomic clock and constantly transmits the GPS time, which is based on the number of seconds elapsed since midnight on 6th January 1980.

With several satellites broadcasting a time code and their location, NAVSTAR GPS works in a similar manner to the original GEE and LORAN radio navigation systems, but it uses three dimensions. Unlike these systems, it provides a location in three physical dimensions. As such, the equations used to locate a receiver's position are more complicated. As well as the error e , introduced by the difference between the receiver's simple clock and the atomic clock on each satellite, there are three variables to solve: x , y and z . If t_1 is the time taken for a signal to arrive from a satellite whose position is known as (x_1, y_1, z_1) , then:

$$t_1 = \frac{\sqrt{(x-x_1)^2 + (y-y_1)^2 + (z-z_1)^2}}{c} + e$$

As this equation has four variables (x, y, z, e), it requires four sets of data, and so four satellites, to solve. Once a GPS receiver has located four

satellites it can measure t_1, t_2, t_3 and t_4 , and the satellites can inform it of their positions $(x_1, y_1, z_1, x_2, y_2, z_2, x_3, y_3, z_3, x_4, y_4, z_4)$. Using this information, it can solve the simultaneous equation required to produce its location (x, y, z) .

PLAYING POLITICS

Despite being developed by the US military for primarily military ends, the NAVSTAR GPS has long been available to the general public. The first significant step towards an open system came in September 1983. On 1st September 1983, Korean Air Lines passenger flight KAL 007, flying from Anchorage to Seoul, strayed miles off its planned course and into Soviet airspace. It was intercepted and shot down by a Soviet Su-15 fighter jet, killing all 269 passengers and crew. Days later, on 16th September, US president Ronald Reagan issued a statement about the incident, proposing that the GPS could be used to avoid similar navigational errors in future. "World opinion is united in its determination that this awful tragedy must not be repeated... the United States is prepared to make available to civilian aircraft the facilities of its global positioning system when it becomes operational in 1988," he said.

This commitment to a widely available system was expanded over the following decade. In 1992, at a meeting of the International Civil Aviation Organisation, the US offered its standard positioning service to the world for the foreseeable future and promised to give at least six years' notice before the system was terminated.

Nonetheless, the NAVSTAR GPS was initially designed to limit its accuracy for civilian users. A function called Selective Availability (SA) was built into the system so that users without special military equipment could not take advantage of its full precision. It functioned by introducing deliberate errors into the data broadcast by each satellite. Military users were able to access the fully accurate system by decrypting a secured second frequency, known as L2, broadcast simultaneously.

During the 1991 Gulf War, however, the US military found itself short of military GPS receivers, and bolstered its inventory with a large number of civilian devices. To increase the accuracy of these units, the SA function was temporarily disabled. On 1st May 2000, President Bill Clinton announced that Selective Availability would be disabled completely. "Threat assessments... conclude that setting SA to zero would have a minimal impact on national security," he said.

This is not to say that the US has removed all obstacles to anyone who wishes to use GPS technology against its military or security interests, though. In the same speech, Clinton noted that the US has "demonstrated the capability to selectively deny GPS signals on a regional basis when... national security is threatened".

ALTERNATIVE SYSTEMS

With the NAVSTAR GPS built, funded and controlled by the US government, several alternative systems have been constructed or proposed. The Russian GLONASS system is similar in that it uses a constellation of 24 satellites. The first working satellites were launched in 1983, but at the moment only 13 are fully operational.

The European Union's European Space Agency (ESA) is also building an alternative system called



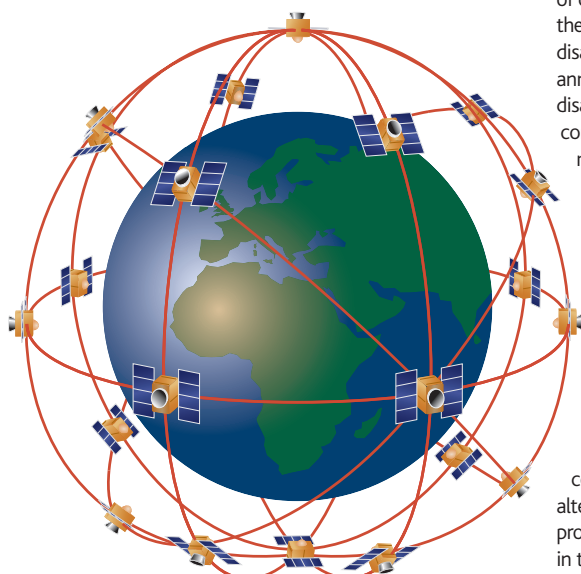
The 19th NAVSTAR Global Positioning System Satellite was launched in 1993 at Cape Canaveral. By December, the full constellation of 24 satellites required for constant worldwide coverage and accuracy was completed

the Galileo Positioning System. The proposed system uses 30 satellites, including three spares. It will provide two publicly available frequencies, unlike the one public and one private frequency system used by GPS and GLONASS, and its orbits are designed to provide better accuracy in northern regions such as Scandinavia. It is due to be completed in 2008.

SIGNAL FAILURES

For all its usefulness, the NAVSTAR GPS is not without its problems. Understandably, the signals received from satellites orbiting miles above the earth are fairly weak. They can be easily obstructed, particularly in cities where high buildings on either side of a road can make getting a signal from enough satellites difficult.

The low strength of the GPS signals leads to another potential problem: the ease with which they can be deliberately obscured or jammed by another, more powerful broadcast on the same frequency. The original GEE system was susceptible to German jamming from 1943, although later GE receivers were able to switch frequencies to avoid jammed signals. In 2003, the online magazine *Phrack* published a detailed explanation of how to build a simple transmitter that could jam NAVSTAR GPS signals, and there is at least one reported case of accidental GPS jamming. In 2003, a television aerial preamplifier on board a boat in Moss Landing, California, disrupted GPS reception in the area for over a month before it was located.



▲ The NAVSTAR GPS system uses 24 satellites orbiting the earth in six orbital paths. To get a 3D position, the user needs to receive signals from four satellites